MSFC-255_ABSTRACT

Testing in Support of Space Fission System Development and Qualification

Mike Houts, Shannon Bragg-Sitton, Anne Garber, Tom Godfroy, Jim Martin, Boise Pearson, Kenny Webster

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Abstract. Extensive data would be required for the qualification of a fission surface power (FSP) system. The strategy for qualifying a FSP system could have a significant programmatic impact. This paper explores potential options that could be used for qualifying FSP systems, including cost-effective means for obtaining required data.

Three methods for obtaining qualification data are analysis, non-nuclear testing, and nuclear testing. It has been over 40 years since the US qualified a space reactor for launch. During that time, advances have been made related to all three methods.

Perhaps the greatest advancement has occurred in the area of computational tools for design and analysis. Tools that have been developed, coupled with modern computers, would have a significant impact on a FSP qualification. This would be especially true for systems with materials and fuels operating well within temperature, irradiation damage, and burnup limits.

The ability to perform highly realistic non-nuclear testing has also advanced throughout the past four decades. Instrumented thermal simulators were developed during the 1970s and 1980s to assist in the development, operation, and assessment of terrestrial fission systems. Instrumented thermal simulators optimized for assisting in the development, operation, and assessment of modern FSP systems have been under development (and utilized) since 1998. These thermal simulators enable heat from fission to be closely mimicked (axial power profile, radial power profile, temperature, heat flux, etc.) and extensive data to be taken from the core region. Both steady-state and transient operation can be tested. For transient testing, reactivity feedback is calculated (or measured in cold/warm criticals) based on reactor temperature and/or dimensional changes. Pin power during a transient is then calculated based on the reactivity feedback that would occur given measured values of temperature and/or dimensional change. In this way non-nuclear testing can be used to provide very realistic information related to nuclear operation. Non-nuclear testing can be used at all levels, including component, subsystem, and integrated system testing. Realistic non-nuclear testing is most useful for systems operating within known temperature, irradiation damage, and burnup capabilities.

Two shortcomings of non-nuclear testing are that radiation damage is not taken into account, and that any modifications needed to enable powering of the thermal simulators could lead to a difference in test article operation and operation of the actual system. Care must also be taken to ensure that reactivity feedback coefficients measured in zero-power critical experiments (or calculated) are applicable to an at-power system. One advantage of realistic non-nuclear testing is that a wide range of reactivity feedback coefficients can be tested. This allows system operation to be tested throughout the full

range of potential as-built coefficients. Operation with coefficients that could occur as a result of off-nominal conditions or aging effects can also be modeled.

Significant capability also exists in the US to perform nuclear testing. FSP fuels and materials are typically chosen to ensure very high confidence in operation at design burnups, fluences, and temperatures. However, facilities exist (e.g. ATR, HFIR) for affordably performing in-pile fuel and materials irradiations if such testing is desired. Ex-core materials and components (such as alternator materials, control drum drives, etc.) could be irradiated in university or DOE reactors to ensure adequate radiation resistance. Facilities also exist for performing warm and cold zero-power criticals. Those tests may be desired for verifying operational (e.g. reactivity feedback coefficients) and safety parameters.

Analysis, non-nuclear testing, and nuclear testing would be needed to qualify a FSP system. Advances have been made in all three areas since the 1965 launch of the SNAP-10A. The capability exists for qualifying a modern FSP system.

MSFC-255 PRESENTATION



Testing in Support of Space Fission System Development and Qualification

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Nuclear Surface Power Systems

- **Power anytime, anywhere on Moon or Mars**
 - Operate in permanently shaded regions
 - Operate through lunar night
 - Operate through Mars global dust storms
 - Operate at high Martian latitudes
 - Extensible for operation anywhere in solar system or beyond
 - Site Preparation, In-Situ Resource Utilization, Propellant Production, Fabrication, Life support, Communication, Mobility, Deep Drilling
- Nuclear technology useful anywhere in space
 - Not dependent on available sunlight





Previous Human Lunar/Mars Power Studies. Total Power Requirements 10 – 100 kWe. Option for Multiple Power Units.

LUNAR						
Studies	**Crew Size**	**Power Need**	**Power Type**	**Mass (mt)**	**Volume (m^3)**	**Comments**
1989 Office of Exploration Technical Report	4 to 12	30 kWe-avg; 50 kWe-peak;	Nuclear reactor with power conv. Unit	4	27	
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Planetary Surface Missions: Continuum of Energy Needs



Now: 290 We Deep Space

General Purpose Heat Source - Radioisotope Thermoelectric Generator (GPHS-RTG) uses 18 Pu-238 fueled GPHS modules

GPHS modules will be used by the 110 We Multi-Mission RTG (MMRTG, 8 modules) and the 110 We Stirling Radioisotope Generator (SRG, 2 modules)



1 kWe Radioisotope Surface (Rover or Stationary)

Stirling energy conversion could allow 1 kWe to be generated using 18 GPHS modules (same # modules as 290 We GPHS-RTG)



10-100 kWe Fission Surface

Not affected by Pu-238 availability concerns

Robust, power-rich environment anytime / anywhere



100 – 1000 kWe Fission Surface

Significant human presence on moon or Mars. Advanced human and robotic activities

Extensive In-Situ Resource Utilization. Reduce propellant and consumable cost

Closed life support systems

Thermoelectric

Stirling

Brayton

Advanced

MMRTG selected for Mars '09

Existing Heat Source Near-Term Option

Existing Technology Near-Term Option

Feasible
Technology development needed

Focus on "Workhorse" System Concept

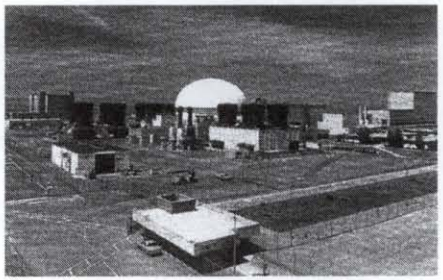


- **Workhorse Definition**
 - Workhorse system is available/desirable once power requirements cannot be met by radioisotopes and/or stored energy. Desired module power level (based on previous studies) 10 – 40 kWe
- **Power level**
 - Fit on lander(s) to be developed for lunar exploration
 - Trade cost, technology risk, programmatic risk, and power level
- **Deployment**
 - 2020 or before
 - Anywhere on Moon, readily extensible to Mars
- **Mass**
 - Deploy using vehicles and equipment that will be developed for lunar exploration. Current assumed maximum allowable mass ~5000 kg.
- **Operation**
 - Initial system provides operational data to qualify for very long life (RTG, SIRTF analog)
 - Extensible to Mars operation
 - Shield to robotic requirements, regolith used to provide additional shielding

➢ **Minimize program risk. Minimize cost and difficulty of getting from current state to a flight qualified system. System must be safe, reliable, and affordable in a cost-constrained environment**

Workhorse System Must Be Affordable

- A surface power system must be safe.
- A surface power system must also have adequate performance, reliability, and lifetime, and meet mass and stowed volume constraints.
- Once basic criteria are met, cost becomes the primary driver.
- JIMO / Prometheus-1: 20 year life; 208 kWe; Cat 1; Refractory metal fuel clad; Potential for refractory metal vessel; high temperature fuel/clad operation; overseas irradiation testing (JOYO), two ground tests, two flight units, power conversion - $3.6B
- Fast Flux Test Facility (400 MWt, fast spectrum, sodium, research) – $3.0B in FY07 $$
- 1371 MWe Commercial Light Water Reactor - $2.2B
- 2-3 MWt TRIGA reactor (fully installed/operational, research capability, no power conversion) < $50M
- Search for innovative approaches to reducing FSP development and utilization cost. Devise cost-competitive system options.







~ $3B (JIMO, FFTF, LWR)

"Modest" Space Reactor?

< $50M (TRIGA)

Development and Qualification Testing for FSP



- Use demonstrated technologies and well qualified fuels and materials to facilitate FSP system qualification.

- Qualification testing strategy should be optimized.

- Robust, affordable test program needed to provide high confidence in mission success.

- Information for qualifying, launching, and operating an FSP system obtained from several sources.
 - Component / subsystem tests (both in-pile and non-nuclear)
 - Cold and hot nuclear criticality tests
 - System modeling/simulations
 - "Simple" non-nuclear system tests
 - High fidelity non-nuclear system tests.

- The fidelity of non-nuclear tests can be extremely high, if desired. The maximum achievable fidelity likely exceeds that required for development and qualification. The optimum desired level of fidelity should be determined early in the program.

Development and Qualification Testing for FSP



- Focus on information required for qualification and operation.

- Use qualified fuels and materials to minimize need for additional fuels and materials testing.
 - Perform component irradiations as needed.

- Verify nuclear operating characteristics using cold and warm zero-power criticals.

- Design system to minimize need to obtain data from a high power integrated system ground nuclear test.
 - Design to be insensitive to parameters that could only be obtained from such testing.
 - Devise methods for validating codes.

High-Fidelity Non-Nuclear Testing



- Instrumented thermal simulators and facility designed to match axial and radial power profile.
 - "Nuclear" profile obtained from zero-power criticals or analysis.
 - Data (temperature, pressure, flow, strain) gathered throughout the system during non-nuclear test.

- All important parameters (temperatures, geometry, reactivity feedback coefficients) are measured.
 - Required software uses measured data, not calculated.
 - Not a "simulation" in the traditional sense of the word.

- Transient testing is one application.
 - Temperature and geometry changes within the core are measured following transient initiation.
 - Reactivity effects are determined using reactivity feedback coefficients (obtained from zero-power criticals or analysis).
 - Power to thermal simulators adjusted as required.

Strengths Associated with High Fidelity Non-Nuclear Testing



1. **The system can be highly instrumented, allowing temperature, strain, and other measurements to be taken throughout the reactor.**

2. **Failure modes can be more extensively tested. Transients or events that would not be allowed in a full-power ground nuclear test can be tested.**

3. **The system can be fully inspected following testing, and the cause of failures can be more readily determined. Imminent failures can also be identified. It is difficult, costly, and time-consuming to inspect a system that has been tested with nuclear heat, and inspection is limited to that which can be done in a hot cell.**

4. **The full, integrated system can be tested using non-nuclear heat.**

5. **Cost/Schedule. "High Fidelity" non-nuclear testing is significantly less expensive than full-power ground nuclear testing. Turn-around time is also much shorter.**

Concerns Associated with High Fidelity Non-Nuclear Testing



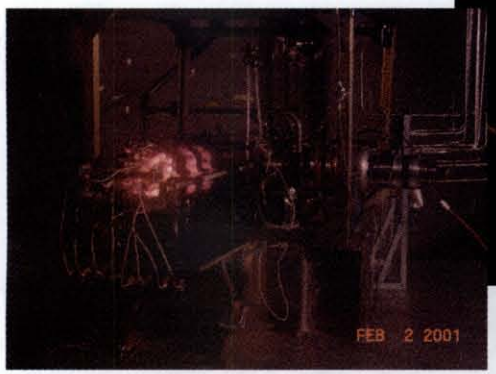
1. **Penetrations needed to provide power to the thermal simulators may be non-prototypic. Calculations and experiments would need to be used to determine any thermal or structural effects from the leads or their sheaths. In the worst case, the flight unit would need to be designed to include dummy penetrations.**

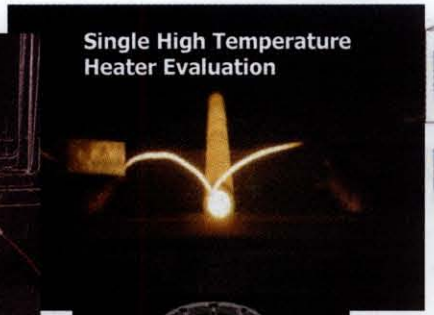
2. **It can be difficult to mimic internal heating in some components (e.g. clad). The FSP systems under consideration operate at very low power density, which helps mitigate this issue.**

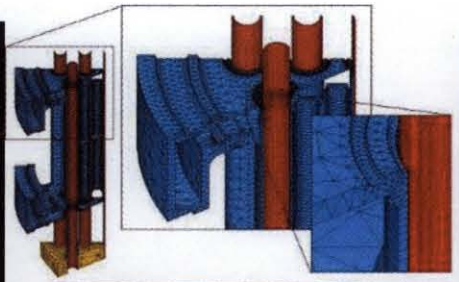
3. **Radiation damage effects are not present in high fidelity integrated non-nuclear system testing. Radiation damage effects would be assessed in separate component / subsystem irradiations. Effects will be mitigated by system design and the low system neutron fluence.**

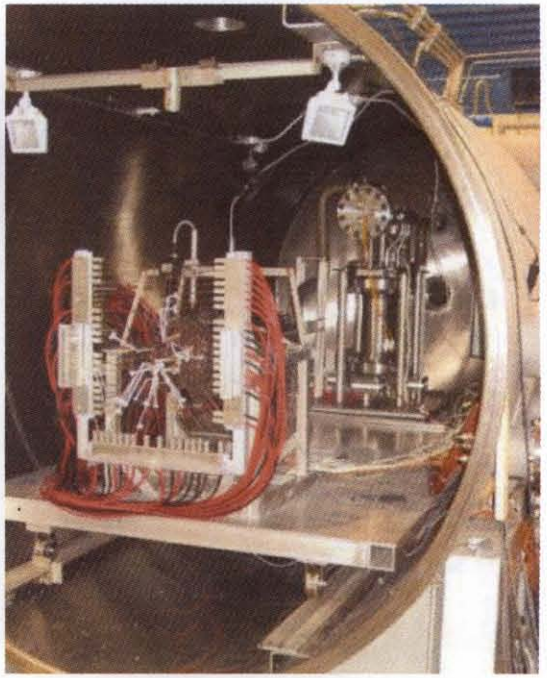
4. **Axial power profile is assumed constant (axial power shape not affected by total power).**

Realistic Non-Nuclear Testing for Thermal, Structural, Heat Transfer, System Integration, and Safety

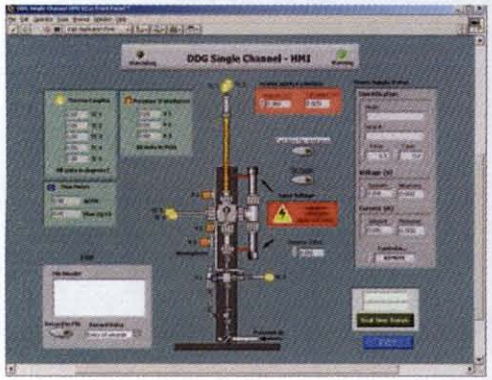






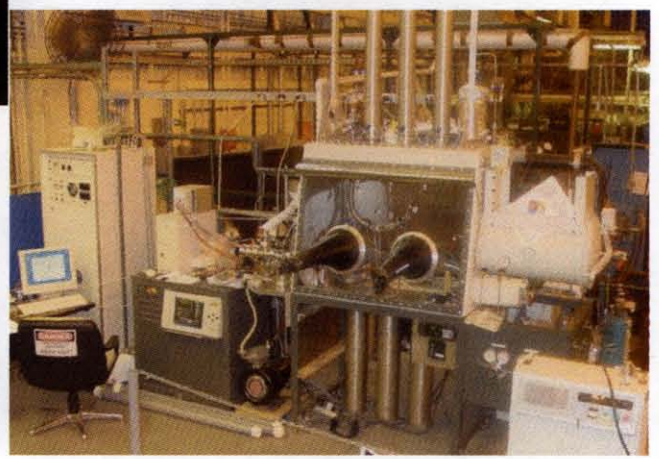


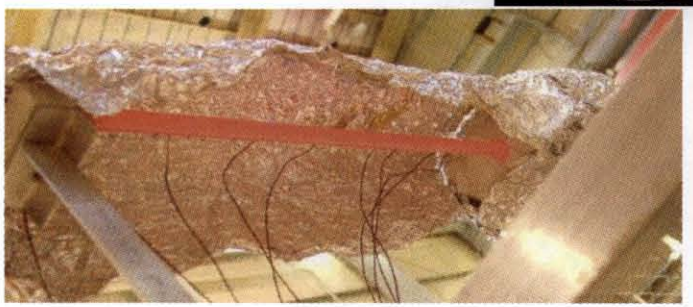






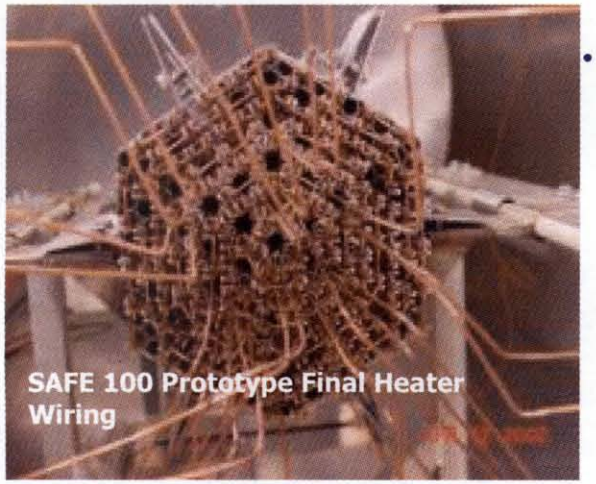








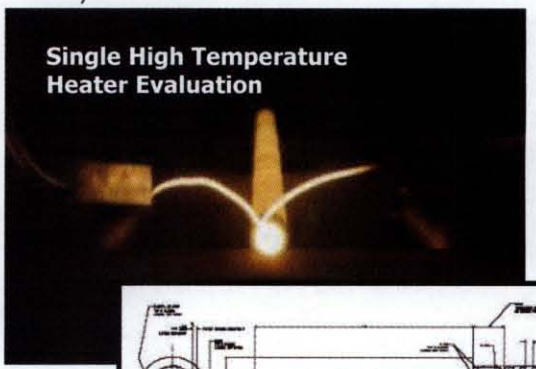
Thermal Simulators

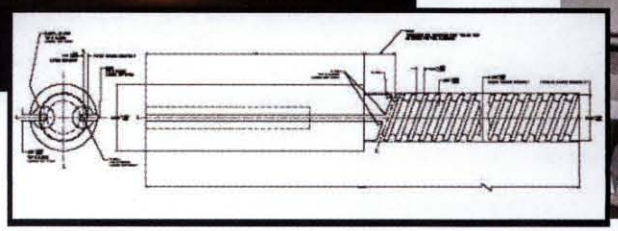


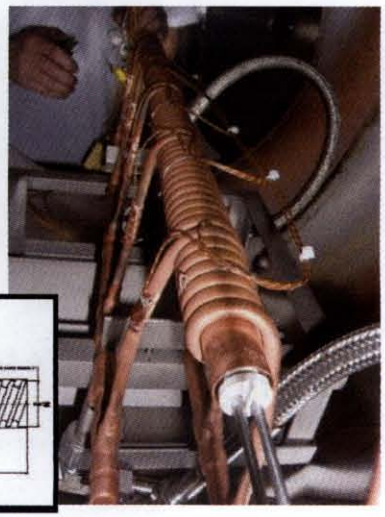




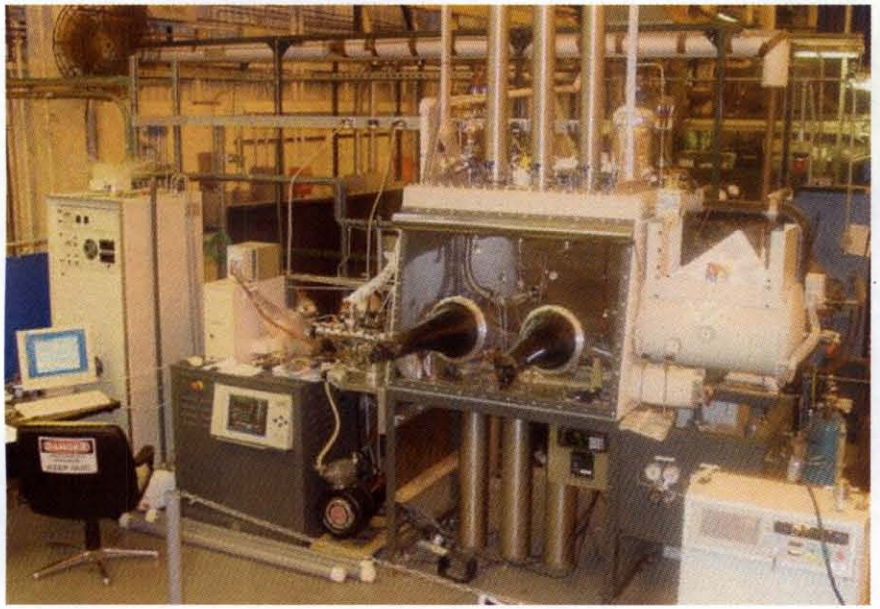
- Multiple concepts (shaped graphite, spiral wound, carbon fibers, brazed, etc..)
- Simulator design is a function of reactor concept. Demonstrated following parameters (individually, not necessarily an integrated assembly) :
 - High temps – demonstrated to 1500 deg C
 - High power densities – demonstrated 5 KW per pin (limitation is ability to remove heat from simulator) – Demonstration of carbon fiber braid
 - Long life cycles – demonstrated over 2000 hours and on-going
 - Axial power profiling – demonstrated distribution
 - Small pin diameters – demonstration of 0.65 cm (~SP 100 fuel pin size)
 - Materials contamination/compatibility and pin conductivity matching – demonstrated ability to "braze within sheath" – sheath same material as core clad and provides ability to match conductivity
 - Integrated 183 pins in footprint of 25.4 cm (10 inch) by 30.5 cm (12 inch)





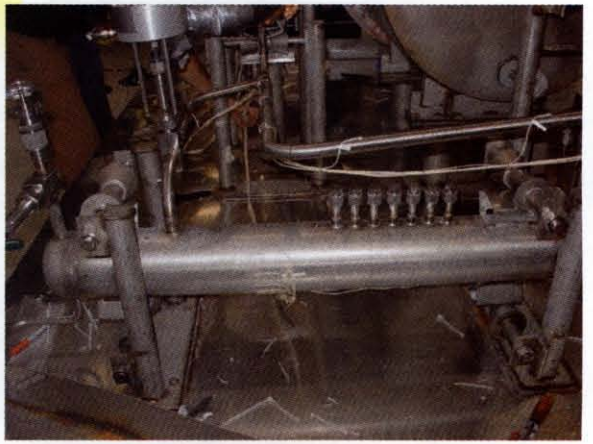


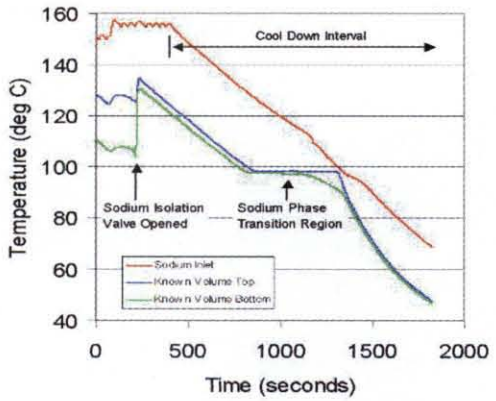
Alkali Metal Handling



Purification and Manipulation of Alkali Metals

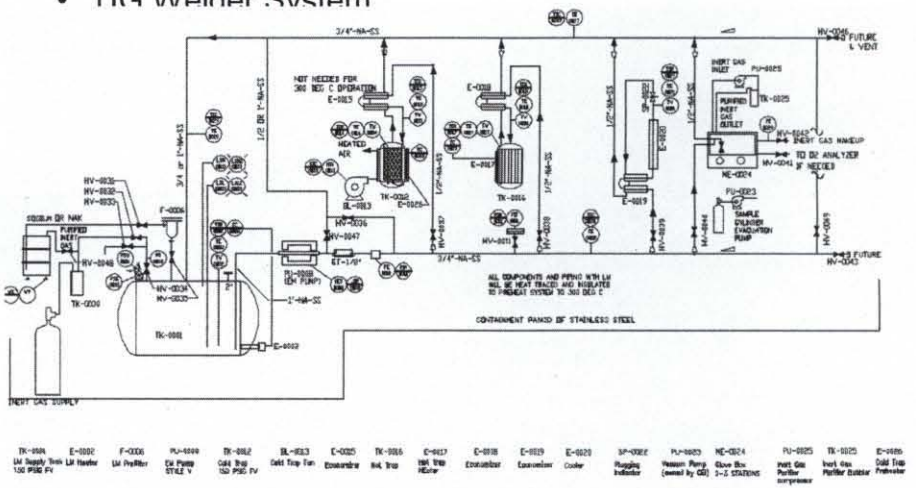
- Achieved <1 ppm Oxygen and Water Vapor
- Experience with Handling NaK, Na and Li
- High Purity Argon Distribution System
- Dri-Train and Ni-Train.
- High Vacuum System ($<10^{-6}$ torr)
- TIG Welder System



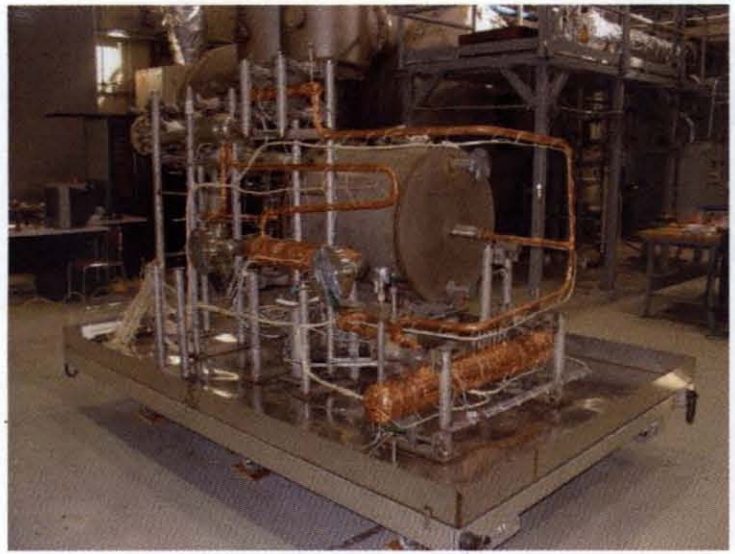


Sodium Transfer

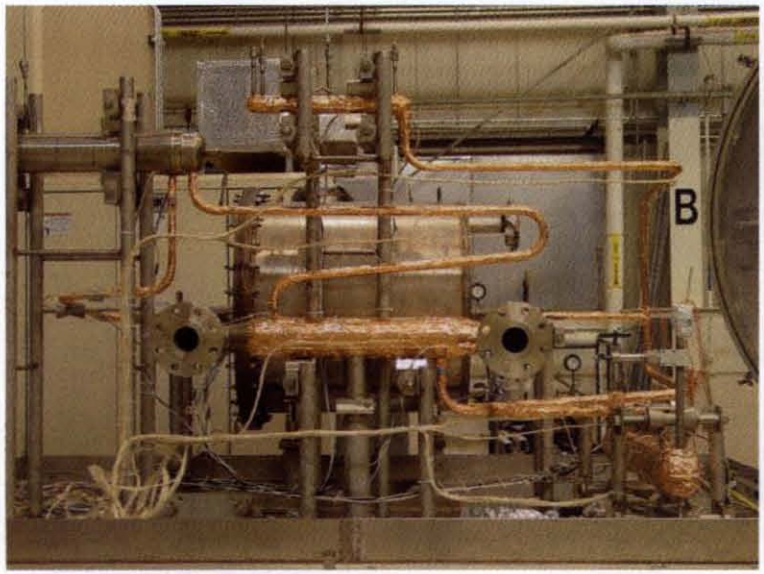
Sodium Purification System

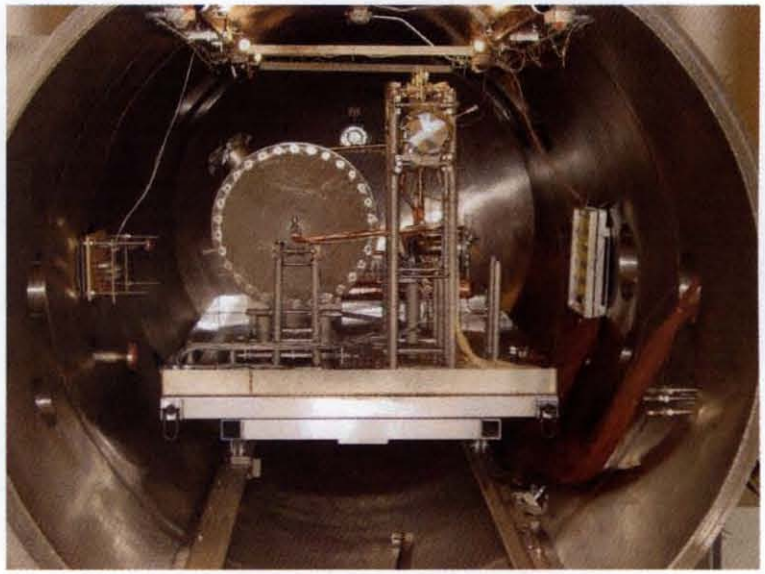


Fission Surface Power Primary Test Circuit (FSP-PTC)









Observations

Fission surface power systems have many attributes that could enhance or enable Vision for Space Exploration missions.

Previous and ongoing experience could facilitate development of affordable "workhorse" FSP systems.

Near-term work can reduce the technical and programmatic risk of FSP systems.

FSP qualification strategy can be optimized for effectiveness and affordability.

FSP systems may reduce overall program risk for certain applications.



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 - High fidelity non-nuclear system tests.

- The fidelity of non-nuclear tests can be extremely high, if desired. The maximum achievable fidelity likely exceeds that required for development and qualification. The optimum desired level of fidelity should be determined early in the program.

Development and Qualification Testing for FSP



- Focus on information required for qualification and operation.

- Use qualified fuels and materials to minimize need for additional fuels and materials testing.
 - Perform component irradiations as needed.

- Verify nuclear operating characteristics using cold and warm zero-power criticals.

- Design system to minimize need to obtain data from a high power integrated system ground nuclear test.
 - Design to be insensitive to parameters that could only be obtained from such testing.
 - Devise methods for validating codes.

High-Fidelity Non-Nuclear Testing



- Instrumented thermal simulators and facility designed to match axial and radial power profile.
 - "Nuclear" profile obtained from zero-power criticals or analysis.
 - Data (temperature, pressure, flow, strain) gathered throughout the system during non-nuclear test.

- All important parameters (temperatures, geometry, reactivity feedback coefficients) are measured.
 - Required software uses measured data, not calculated.
 - Not a "simulation" in the traditional sense of the word.

- Transient testing is one application.
 - Temperature and geometry changes within the core are measured following transient initiation.
 - Reactivity effects are determined using reactivity feedback coefficients (obtained from zero-power criticals or analysis).
 - Power to thermal simulators adjusted as required.

Strengths Associated with High Fidelity Non-Nuclear Testing



1. **The system can be highly instrumented, allowing temperature, strain, and other measurements to be taken throughout the reactor.**

2. **Failure modes can be more extensively tested. Transients or events that would not be allowed in a full-power ground nuclear test can be tested.**

3. **The system can be fully inspected following testing, and the cause of failures can be more readily determined. Imminent failures can also be identified. It is difficult, costly, and time-consuming to inspect a system that has been tested with nuclear heat, and inspection is limited to that which can be done in a hot cell.**

4. **The full, integrated system can be tested using non-nuclear heat.**

5. **Cost/Schedule. "High Fidelity" non-nuclear testing is significantly less expensive than full-power ground nuclear testing. Turn-around time is also much shorter.**

Concerns Associated with High Fidelity Non-Nuclear Testing



1. **Penetrations needed to provide power to the thermal simulators may be non-prototypic. Calculations and experiments would need to be used to determine any thermal or structural effects from the leads or their sheaths. In the worst case, the flight unit would need to be designed to include dummy penetrations.**

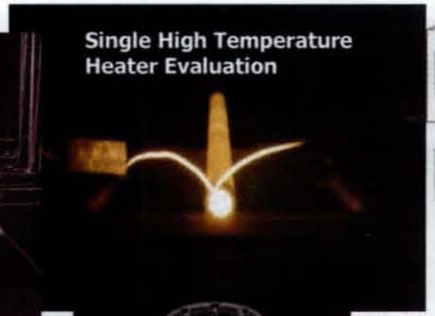
2. **It can be difficult to mimic internal heating in some components (e.g. clad). The FSP systems under consideration operate at very low power density, which helps mitigate this issue.**

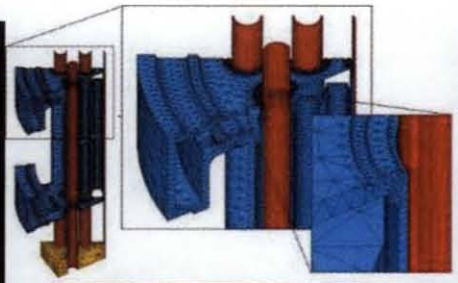
3. **Radiation damage effects are not present in high fidelity integrated non-nuclear system testing. Radiation damage effects would be assessed in separate component / subsystem irradiations. Effects will be mitigated by system design and the low system neutron fluence.**

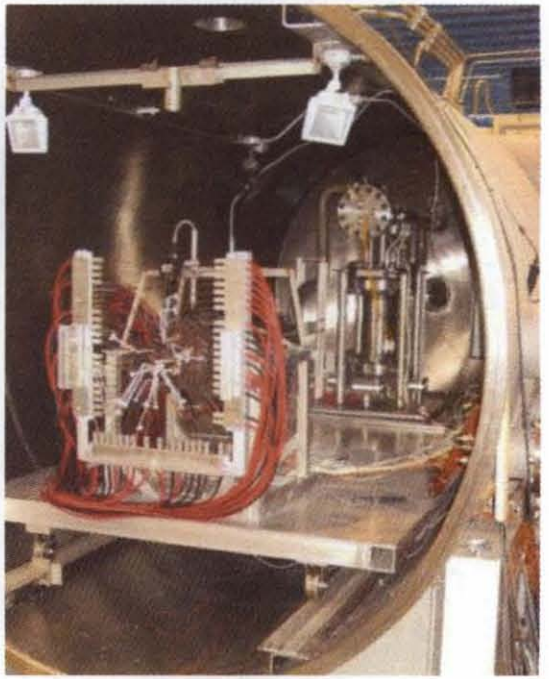
4. **Axial power profile is assumed constant (axial power shape not affected by total power).**

Realistic Non-Nuclear Testing for Thermal, Structural, Heat Transfer, System Integration, and Safety

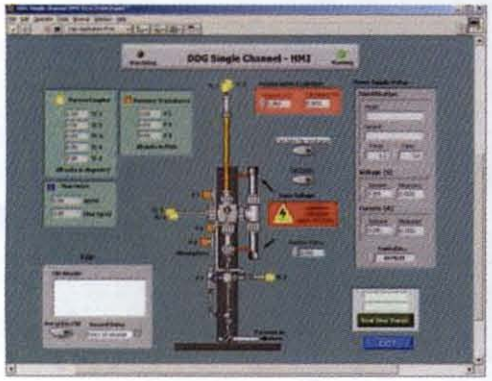






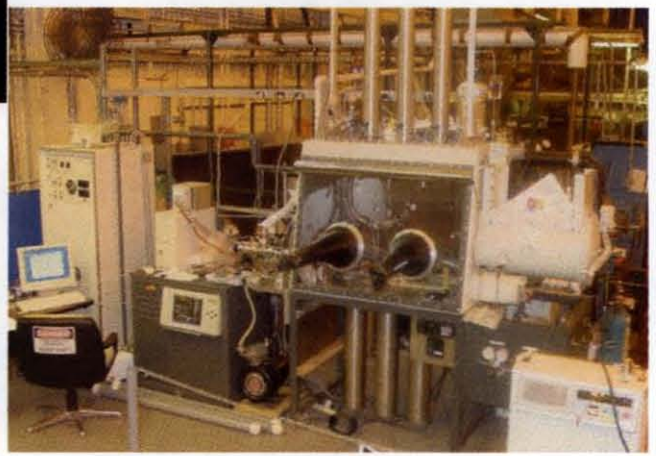


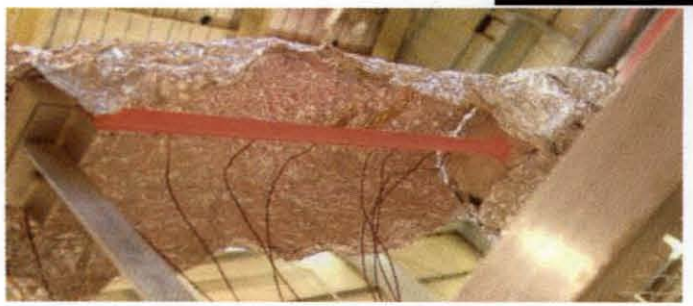






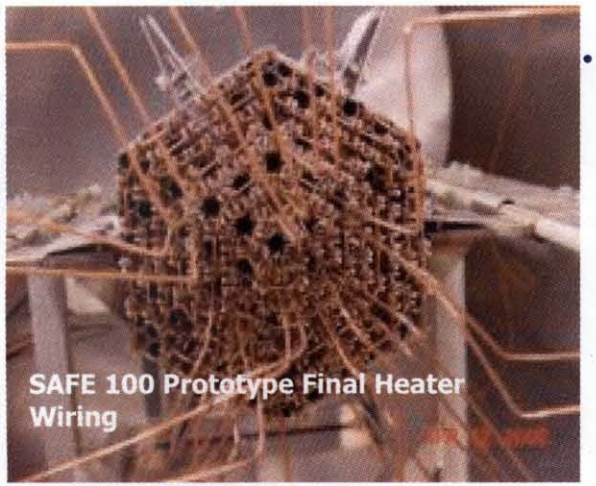


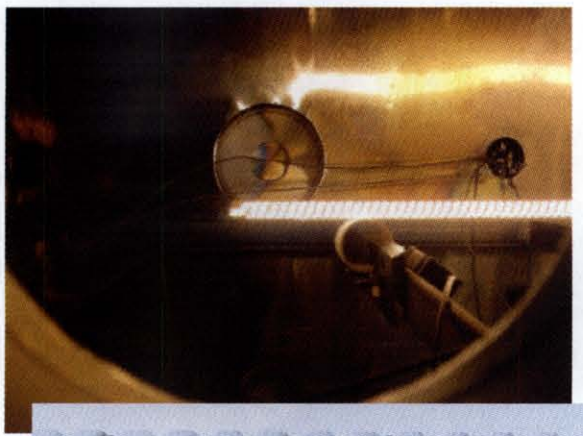






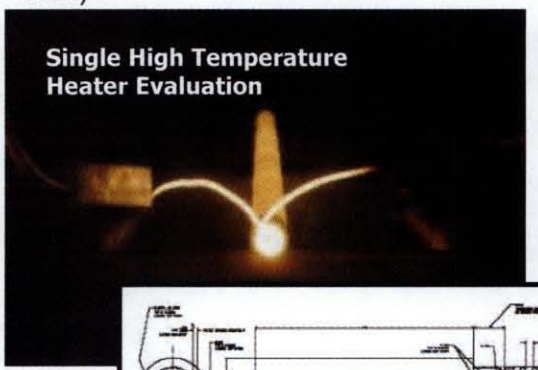
Thermal Simulators

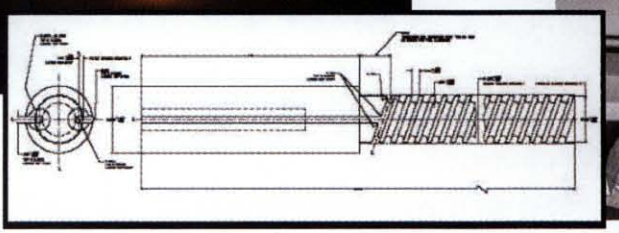


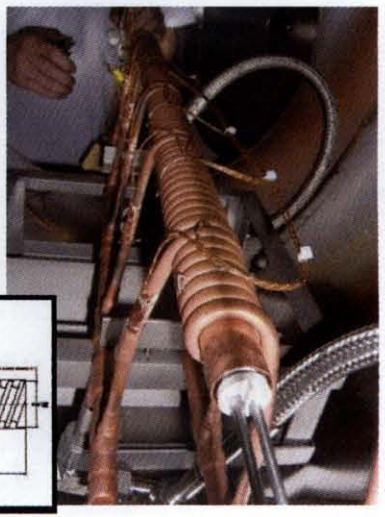




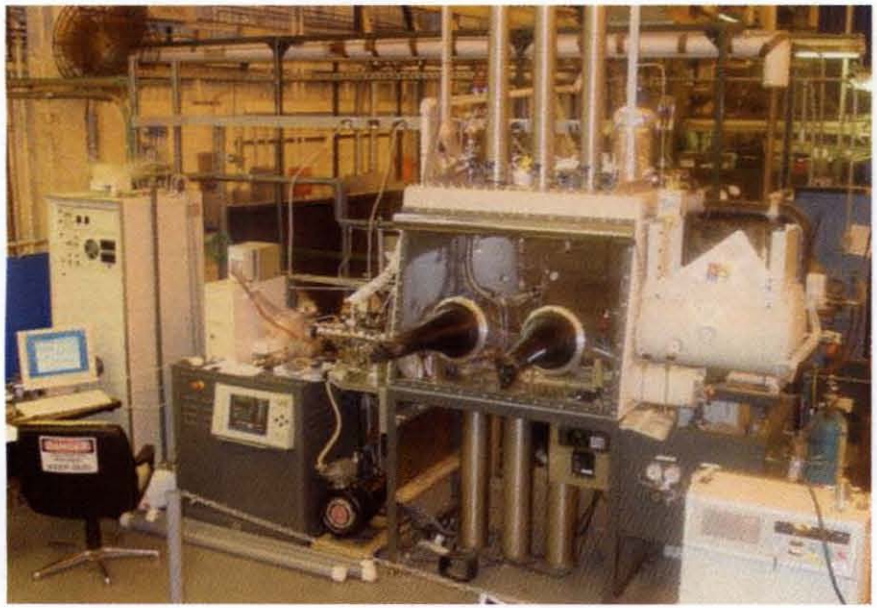
- Multiple concepts (shaped graphite, spiral wound, carbon fibers, brazed, etc..)
- Simulator design is a function of reactor concept. Demonstrated following parameters (individually, not necessarily an integrated assembly) :
 - High temps – demonstrated to 1500 deg C
 - High power densities – demonstrated 5 KW per pin (limitation is ability to remove heat from simulator) – Demonstration of carbon fiber braid
 - Long life cycles – demonstrated over 2000 hours and on-going
 - Axial power profiling – demonstrated distribution
 - Small pin diameters – demonstration of 0.65 cm (~SP 100 fuel pin size)
 - Materials contamination/compatibility and pin conductivity matching – demonstrated ability to "braze within sheath" – sheath same material as core clad and provides ability to match conductivity
 - Integrated 183 pins in footprint of 25.4 cm (10 inch) by 30.5 cm (12 inch)





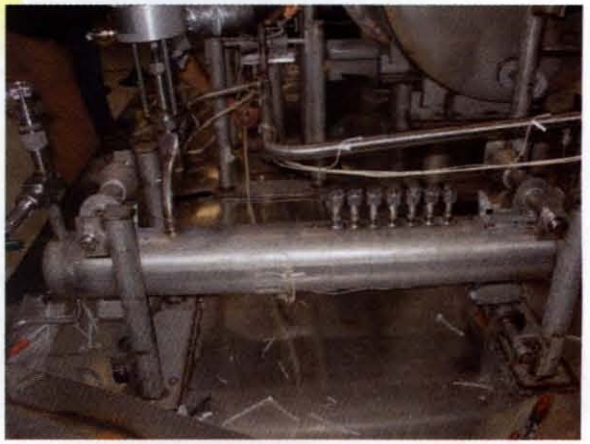


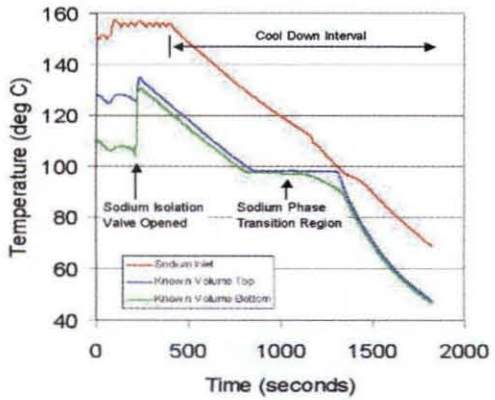
Alkali Metal Handling



Purification and Manipulation of Alkali Metals

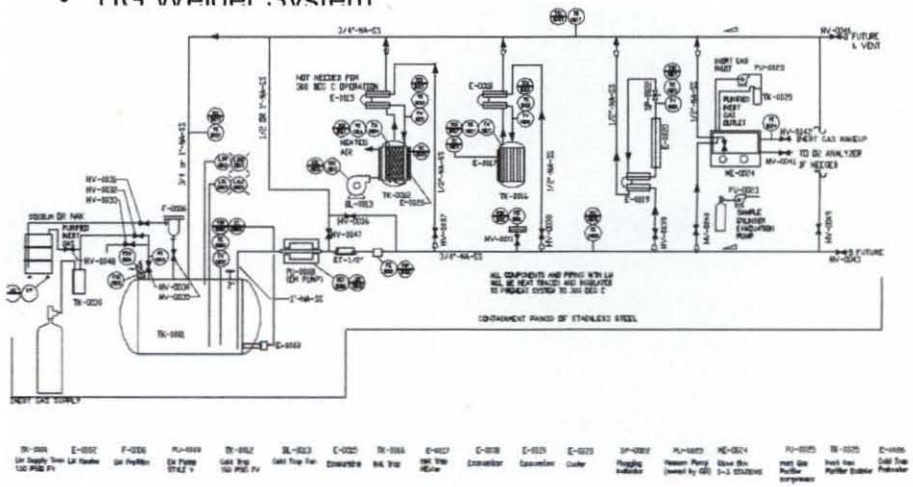
- Achieved <1 ppm Oxygen and Water Vapor
- Experience with Handling NaK, Na and Li
- High Purity Argon Distribution System
- Dri-Train and Ni-Train.
- High Vacuum System ($<10^{-6}$ torr)
- TIG Welder System



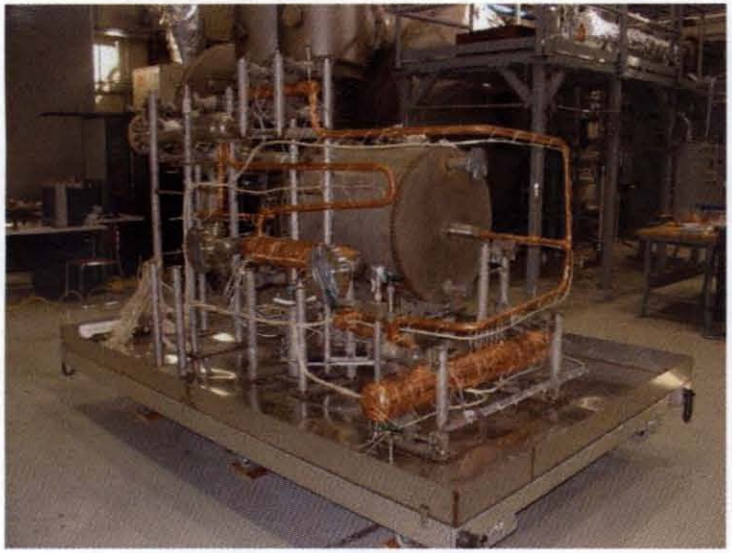


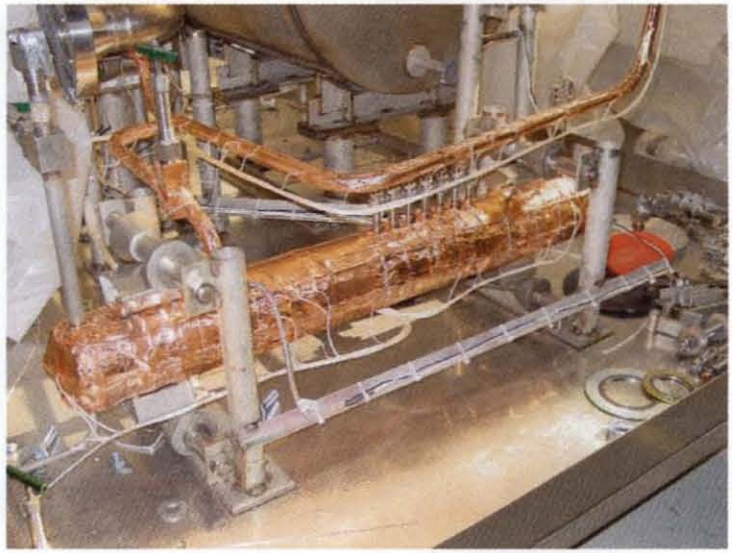
Sodium Transfer

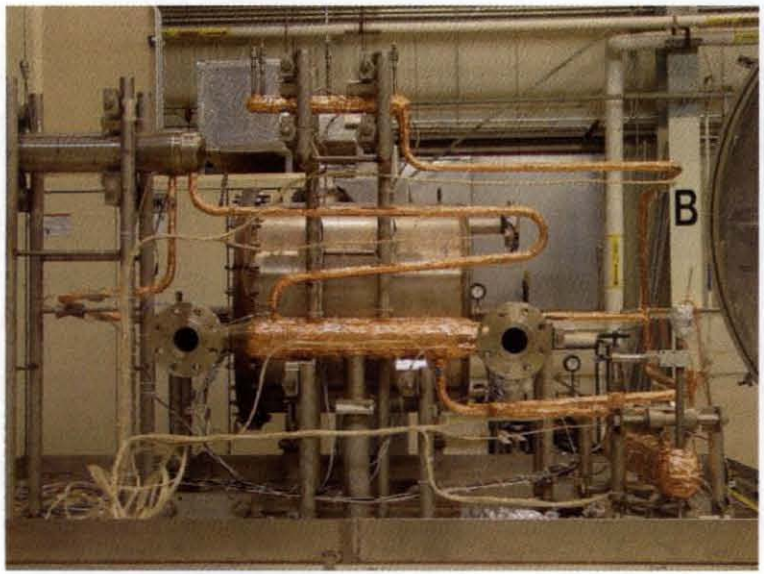
Sodium Purification System

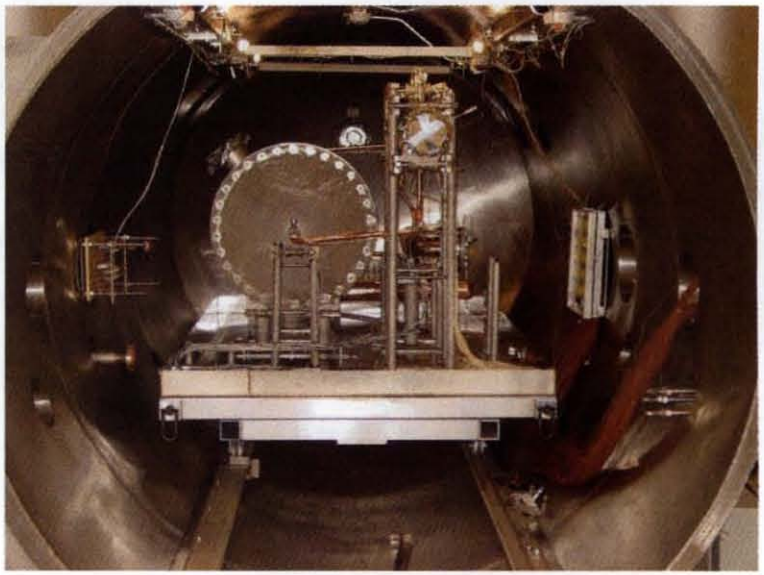


Fission Surface Power Primary Test Circuit (FSP-PTC)









Observations



Fission surface power systems have many attributes that could enhance or enable Vision for Space Exploration missions.

Previous and ongoing experience could facilitate development of affordable "workhorse" FSP systems.

Near-term work can reduce the technical and programmatic risk of FSP systems.

FSP qualification strategy can be optimized for effectiveness and affordability.

FSP systems may reduce overall program risk for certain applications.